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Impact of Arctic shelf summer stratification on Holocene climate variability

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ABSTRACT

Understanding the dynamic of freshwater and sea-ice export from the Arctic is crucial to better comprehend the potential near-future climate change consequences. Here, we report nitrogen isotope data of a core from the Laptev Sea to shed light on the impact of the Holocene Siberian transgression on the summer stratification of the Laptev Sea. Our data suggest that the oceanographic setting was less favourable to sea-ice formation in the Laptev Sea during the early to mid-Holocene. It is only after the sea level reached a standstill at around 4 ka that the water column structure in the Laptev Sea became more stable. Modern-day conditions, often described as "sea-ice factory", were reached about 2 ka ago, after the development of a strong summer stratification. These results are consistent with sea-ice reconstruction along the Transpolar Drift, highlighting the potential contribution of the Laptev Sea to the export of freshwater from the Arctic Ocean.

1. Introduction

The Arctic climate is changing at a rapid pace; in fact, this region warms faster than any other on the globe because of polar amplification (Manabe and Stouffer, 1980; Serreze and Barry, 2011). One major impact of the observed warming is the dramatic increase in the sea-ice melt season and the consequent reduction of sea-ice cover (Comiso et al., 2008; Perovich and Richter-Menge, 2009). These changes in the sea-ice dynamic directly influence the export of sea-ice via Fram Strait, which accounts for about 25% of the total freshwater export from the Arctic (Serreze et al., 2006). The Arctic sea-ice export through Fram Strait plays an important role in the global climatic system as it influences the freshwater balance of the northern North Atlantic (Curry, 2005; Sciences et al., 2006), which in turn affects the strength of the Atlantic meridional overturning circulation (Belkin et al., 1998; Dickson et al., 1988; Ionita et al., 2016).

From all Siberian shelf seas, the Laptev Sea is thought to contribute the largest fraction of sea-ice export towards Fram Strait (Krumpen et al., 2016; Reimnitz et al., 1994; Zakharov, 1966) (Fig. 1). It was suggested that 20% of the sea-ice transported via the Transpolar Drift (TD) through Fram Strait is produced in the Laptev Sea (Rigor and Colony, 1997) and recent estimates suggested that the Laptev Sea was exporting an area of sea-ice equivalent to 41% of the sea-ice exported via Fram Strait (Krumpen et al., 2013). Thus, it is critical to understand the longer-term dynamics of sea-ice production within the Laptev Sea in order to better apprehend the potential near-future change in sea-ice export via Fram Strait. The presence of a relatively fresh surface layer promotes the formation of ice in the Laptev Sea, which, in turn, releases brines and contributes to the formation of the shelf halocline layer, a critical "buffer" between the surface and the saltier bottom layer (Dmitrenko et al., 2009; Krumpen et al., 2013). The resulting stratification is strong enough to persist through the whole year as the long term probability for winter convection to reach the seafloor is only about 20% (Dmitrenko et al., 2012; Krumpen et al., 2011). The strength of stratification is controlled by the summer

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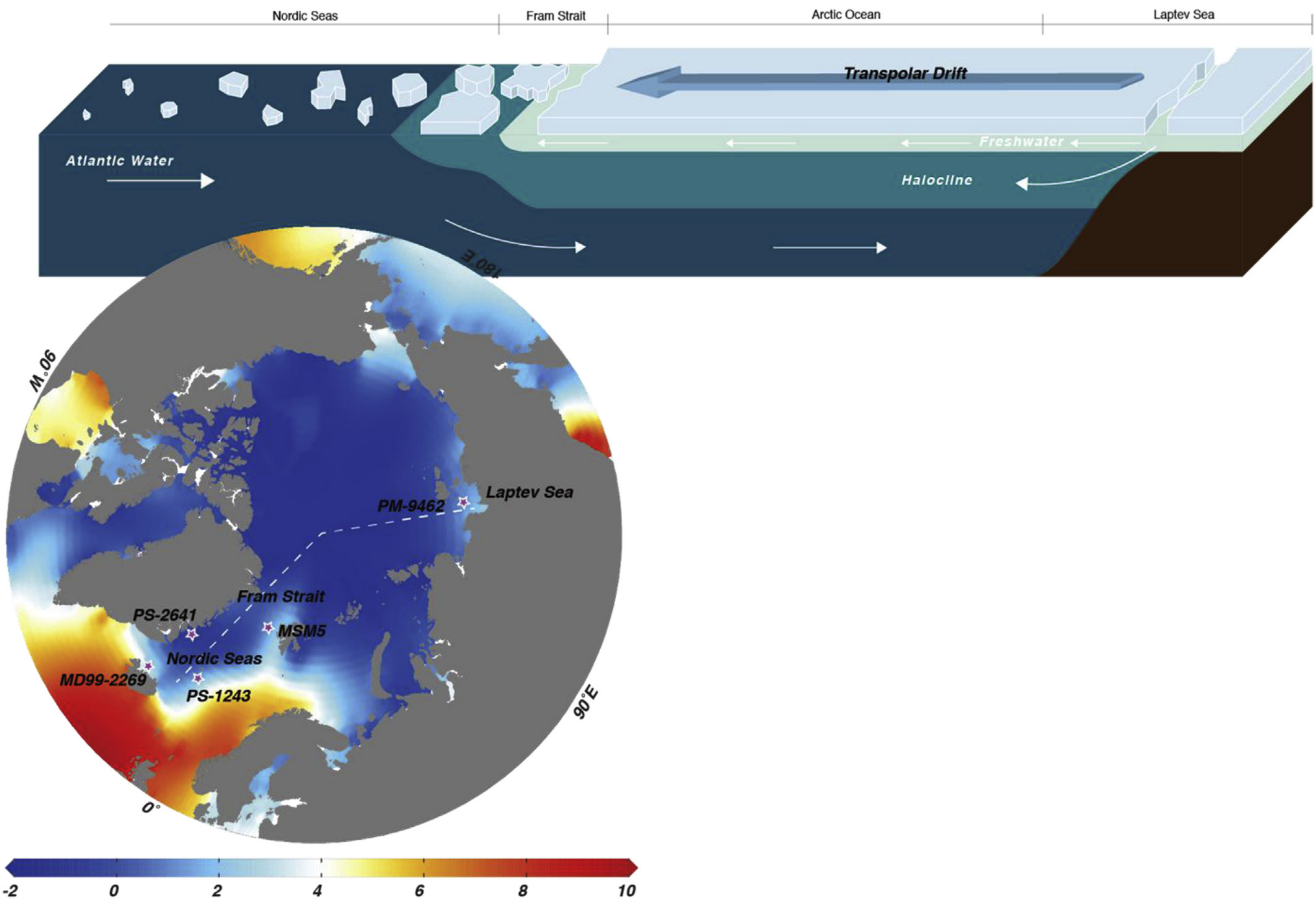

Fig. 1. The Transpolar Drift system from the Laptev Sea to the Nordic Seas. The upper panel is a depth profile of the different water masses along the white dashed transect on the bottom panel. The color scale on lower panel shows the 1955-2012-averaged sea-surface January temperature (°C) (data from Levitus et al., 2013). Location of the cores discussed in the paper are indicated by stars on the lower panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

atmospheric circulation that influences the freshwater budget of the Laptev Sea (Dmitrenko et al., 2005, 2008; Thibodeau et al., 2014) and preconditions the next winter sea-ice production (Bauch et al., 2012; Dmitrenko et al., 2010; Thibodeau and Bauch, 2016). Despite the widely recognized climatic importance of the Laptev Sea stratification, we possess little information on its longer-term evolution through the Holocene, i.e., during the past 11 ka when post-glacial sea level rise caused dramatic environmental changes on the circum-arctic shelves (Bauch et al., 2001b), and on the role it might have played on the gradual establishment of modern Arctic climate.

Recent work based on geochemical proxies reconstructed the Holocene variability in the production of sea-ice algae over the Laptev Sea (Hörner et al., 2016). They observed a general increasing trend superimposed by short-time variability that was interpreted as representing Bond cycles (1500 ± 500 ka), which are generally considered to be linked to changes in solar activity (Bond et al., 1997). However, the 1500-year cycle in Arctic Oscillation and Arctic sea-ice drift was previously found distinct from the solar irradiance cycle and it was hypothesized that internal variability or indirect response to low-latitude solar forcing was driving the cycle (Darby et al., 2012). This is actually in line with the original analysis of Bond et al. (2001) who found the last three ice-drift cycles to be discordant with both the Arctic Oscillation and North Atlantic Oscillation dipole anomaly. This highlight the need to investigate other mechanisms that could influence the sea-ice production in the Arctic Ocean over the Holocene, like water column stratification in marginal seas.

Here, we use nitrogen isotope in a well-dated sediment core from the Laptev Sea shelf to reconstruct nutrient utilization and summer stratification. Comparison with proxy of sea-ice algae production is carried-out to investigate the link between the stratification and the variation in sea-ice. We will then implicate our record to sea-ice export, temperature and water stratification proxies along the TD to better understand the potential impact of the Laptev Sea stratification on the larger-scale Arctic climate processes.

2. Regional setting

The Laptev Sea is characterized by an estuarine-like circulation, with freshwater runoff from the Lena River at surface and an inflow of salty modified-Atlantic water at depth. This physical feature exerts a strong control on the biogeochemistry of nutrients, notably nitrate (e.g., Kattner et al., 1999). The strong stratification between surface freshwater and marine-derived bottom water prevent any replenishment of nutrients during summer. Thus, nitrate from winter mixing and from the Lena River is rapidly consumed in the surface water during Arctic summer, leading to very low, but not totally depleted, nitrate concentration at the end of the summer (~0.5 μmol L^{-1}), while bottom water are between 2 and 6 μmol L^{-1} (Thibodeau et al., 2017a). During winter, mixing occurs and

replenishes the surface water with nutrients. The most recent data suggest that the surface water overlying the core today is characterized by nitrate concentration between 1.5 and 2 μmol L^{-1} at the end of the Arctic summer (Fig. 2).

3. Material and methods

3.1. Sediment core and chronology

The 467 cm-long vibrocore PM9462 was raised from 27 m water depth in the east part of the Laptev Sea (73°30.2′N, 136°00.3′E). The sediment core was mainly composed of uniform, nearly black, clayey silt (originally described in Bauch et al., 2001b). The chronology of the core was established based on twelve *Portlandia arctica* ^{14}C measurements (Bauch et al., 2001a). Reservoir age (370 ± 49 ^{14}C yr B.P.) was determined from the shell of living bivalves from the bottom of the Laptev Sea. Linear interpolation was used to estimate the age between each ^{14}C value. The oldest measured age is about 8900 cal yr B.P. (Bauch et al., 2001a). Depending on the sample interval, the resolution of each sample ranges from 104 to 391 cal yr.

3.2. Geochemical and micropaleontological proxies

Multiples proxies were already available for this sediment core; total organic carbon, $\delta^{13}C$ or organic carbon, the aquatic palynomorphs (chlorophyceae and dinoflagellates), grain size and garnet content (Fig. 3). Original data and detailed methods can be found in Bauch et al. (2001b).

3.3. Organic nitrogen isotope

In this study we use, for the first time, the nitrogen content and nitrogen stable isotope ($\delta^{15}N$) to investigate the dynamic of nitrogen over this shelf during the Holocene. Nitrogen stable isotope can be used to reconstruct past changes in the nitrogen cycle (e.g., Altabet and Francois, 1994; Galbraith et al., 2008; Robinson et al., 2004; Tesdal et al., 2013). In ecosystems where nitrogen is not fully assimilated, the $\delta^{15}N$ is directly linked to the isotopic signature of the supply of nitrate and the fractionation caused by its assimilation and thus, can be used to highlight potential change in the relative proportion of nitrate that is consumed (N-utilization) (Riethdorf et al., 2016; Straub et al., 2013; Thibodeau et al., 2017b). However, in the Arctic Ocean, an important caveat to the use of bulk sediment $\delta^{15}N$ exists because sediments can contain significant amounts of inorganic nitrogen that includes ammonium adsorbed onto clay minerals (Müller, 1977; Schubert and Calvert, 2001; Stevenson and Dhariwal, 1959). By removing organic nitrogen from the bulk sediment with a KOBr-KOH solution, it is possible to measure the amount of bound inorganic nitrogen and its isotopic composition (Knies et al., 2007; Schubert and Calvert, 2001). The $\delta^{15}N$ of the organic nitrogen is then obtained by calculation using the inorganic signal and the bulk $\delta^{15}N$ in a mass balance equation. This correction removes the potential bias of inorganic nitrogen. Bulk $\delta^{15}N$ can be altered during burial and early diagenesis, particularly outside of continental margin (Robinson et al., 2012). While it is not possible to unilaterally reject the potential influence of alteration, there is no reasons to suspect large and/or variable alteration of the signal through time as our site was at shallow depth (10–30 m) throughout the Holocene (Bauch et al., 2001b). Finally, since our core was located near the coast for the Holocene, we hypothesise that the surface water was never completely limited in nitrate during that period. This is supported by the current setting, were nitrate are not totally used during summer (Fig. 2). It is important to note that the present distance between the core and the coastline is at its maximum for the Holocene, and thus we can suspect that the quantity of nutrient reaching that position is therefore at its minimum for the Holocene. The last factor, beside N-utilization, that could influence our $\delta^{15}N$ record is the initial signature of the organic material, which can be modified depending on the source of nitrogen (e.g., terrestrial vs marine). Thus, we interpret our $\delta^{15}N$ record as variation in the ratio of terrestrial to marine organic matter, and/or in a change in N-utilization depending on the information gathered from other proxy.

Nitrogen content and isotope ratio for both bulk and inorganic nitrogen were analyzed by elemental analyser isotope ratio mass spectrometer (EA-IRMS). The precision for treated and untreated samples was better than ±0.2‰. Organic nitrogen isotope was calculated by subtracting the inorganic value from the bulk isotopic composition (e.g., Knies et al., 2007). The age model and the other proxies for core PM9462 were originally described by Bauch et al. (2001a, 2001b).

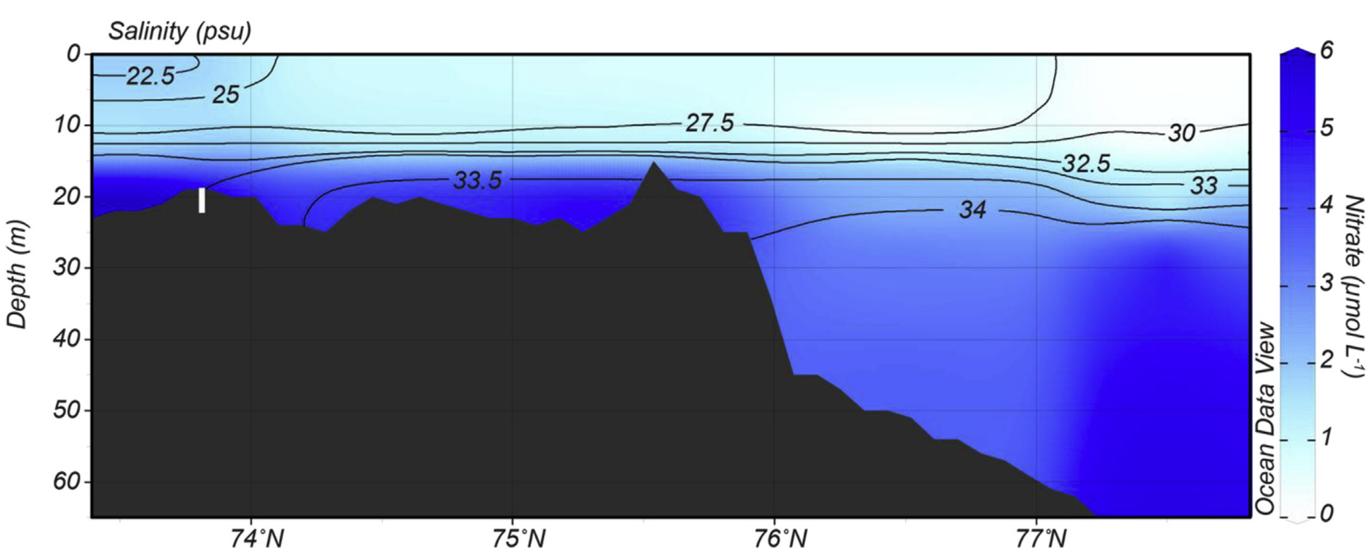

Fig. 2. Depth profile of nitrate concentration (color raster) and salinity (black contours) measured in 2014 (Thibodeau et al., 2017a) at ~131°N, close to the core studied here (represented in white). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

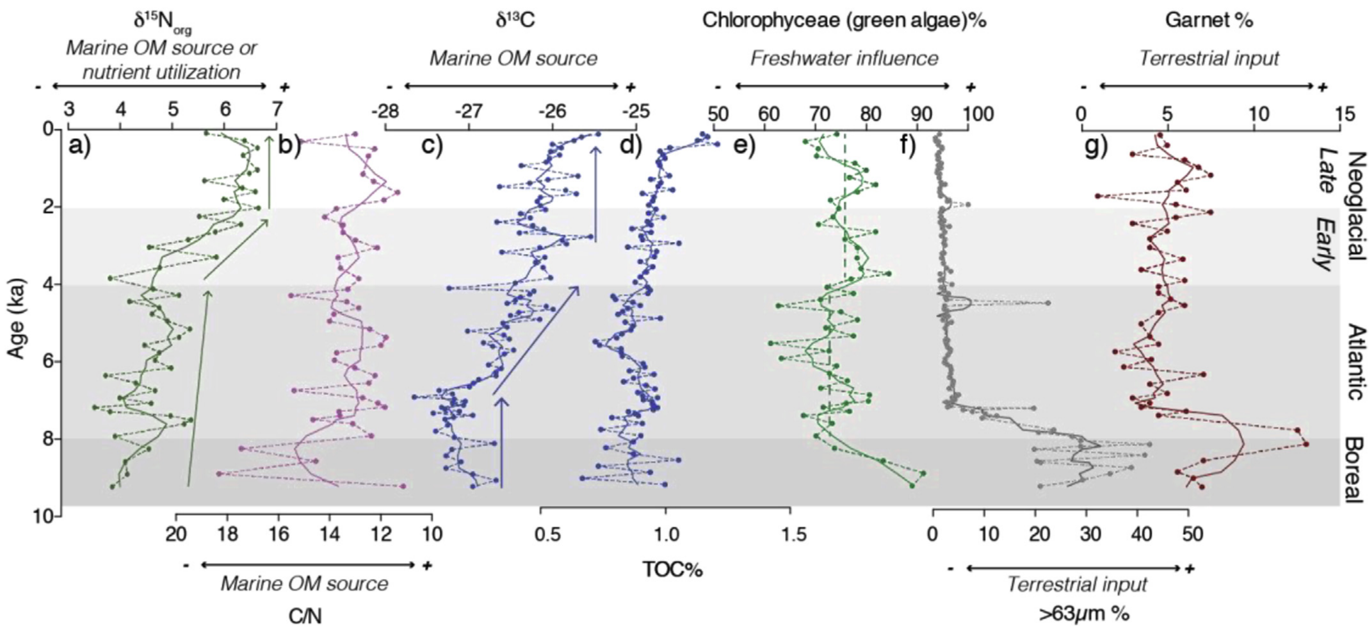

Fig. 3. Sedimentary proxy in core PM9462 in function of the age model: **a)** $\delta^{15}N$ of organic nitrogen (green, in ‰), **b)** carbon to nitrogen ratio (pink), **c)** $\delta^{13}C$ of the organic carbon (blue, in ‰), **d)** total organic carbon (blue, in %), **e)** the proportion of green algae (green, in %), **f)** the proportion of sand (grey, in %) and **g)** the proportion of garnet (red, in %). A 4-neighbors, 2nd order smoothing was applied to all dataset to see the general trend (solid lines). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Results

Three distinct periods characterized core PM9462. The bottom of the core (>8 ka; Boreal period) has a high proportion of terrestrial markers like sand (40%) and garnet (13%), as well as typical terrestrial signatures of $\delta^{13}C_{org}$ (−27‰) and C:N (>15) (Fig. 3). Sand, C/N ratio and total organic carbon notably show a high degree of variability. This part also has the highest proportion of freshwater algae (>70–90% of total algae content). The $\delta^{15}N$ of organic nitrogen is slightly higher than 4‰. The regime transitions from heavily dominated by terrestrial-markers during the Boreal to more marine-influenced conditions in the Atlantic period (8–4 ka); the proportion of sand and garnet decreases dramatically right at the transition and decrease slowly without much variability (sand) or stays constant on average but with a high variability (garnet). The $\delta^{13}C_{org}$ starts increasing gradually toward −26‰ about 1 ka after the transition, while the C:N ratio drops rapidly to ~13 and stays constant on average but with a high variability. Moreover, we observe the lowest proportion of freshwater algae (~70%) and a gradual increase in the isotopic composition of organic nitrogen (Fig. 3). The third period (4–0 ka; Neoglacial period) is characterized by relatively constant terrestrial vs marine markers (sand, garnet, $\delta^{13}C_{org}$, C:N). However, we subdivide this period in two parts (early and late) as there is a sharp increase in the $\delta^{15}N$ around 4 ka and a stabilization (~6.5‰) at around 2 ka (Fig. 3). The Neoglacial is also characterized by statistically significant higher freshwater algae (average = 76.19% ± 0.97, $P < 0.05$; Mann-Whitney test performed with ©Prism7.0d) than the Atlantic period (average = 72.84% ± 1.05). The freshwater algae record is characterized by high variability in the Atlantic and Neoglacial periods.

5. Enhanced nitrogen utilization during the Neoglacial

The proxy data from core PM9462 recorded a mixture of two signals: (1) the shift from terrestrial dominated input to a more marine-influenced organic matter input; (2) change in nutrient utilization due to change in the water column stratification. The first part of the story is well documented over the Laptev and Kara Seas (e.g., Bauch et al., 2001a, 1999; Boucsein et al., 2002; Stein et al., 2004, 2001; 1999; Stein and Fahl, 2000). With the initial transgression of the Laptev Sea, a clear transition during the Atlantic period occurred where: (1) most of the geologic marker of detritic input decreased; (2) the freshwater markers decreased; (3) the proportion of marine organic matter increased (Fig. 3). The latter signal is primarily registered in the $\delta^{13}C_{org}$ record with a trend towards gradually heavier values since c. 7 ka, which is consistent with other geochemical proxies (e.g., Stein et al., 1999). The $\delta^{15}N_{org}$ remained largely constant (4–5‰) during the Boreal and Atlantic period, highlighting the gradual increase in marine-dominated organic matter from the Boreal to the Atlantic (e.g., Stein et al., 2001). This transition to heavier values might be partially masked by a low N-utilization facilitated by the absence of a strong pycnocline during summer, allowing the mixing of surface water with nutrient rich Atlantic-derived waters (Thibodeau et al., 2017a). The masking effect of N-utilization might explain the small discrepancy between the transition in the early part of the Atlantic periods between $\delta^{15}N$ and the other marine/terrestrial markers (Fig. 3). The time between 5 and 8 ka is characterized not only by a constant sea-level rise but also by intense river runoff. That riverine water should have promoted a higher rate of freshwater algae input. However, at our study site we recorded the lowermost amount of these algae during the entire Holocene. A possible explanation for this discrepancy could be that the surface water was slightly saltier than during the Neoglacial. The intense river runoff combined with the sea-level rise could have created a relatively unstable water column and promoted mixing of surface water with deeper water (Fig. 4). This assumption would be coherent with the irregular sedimentation regime observed during the 5–8 ka period, which was attributed to sea-level rise (Bauch et al., 2001a). This is supported by $\delta^{18}O$ values from bivalve shells, which found the highest summer salinity value of the Holocene at around 4 ka (Mueller-Lupp et al., 2004). On the other

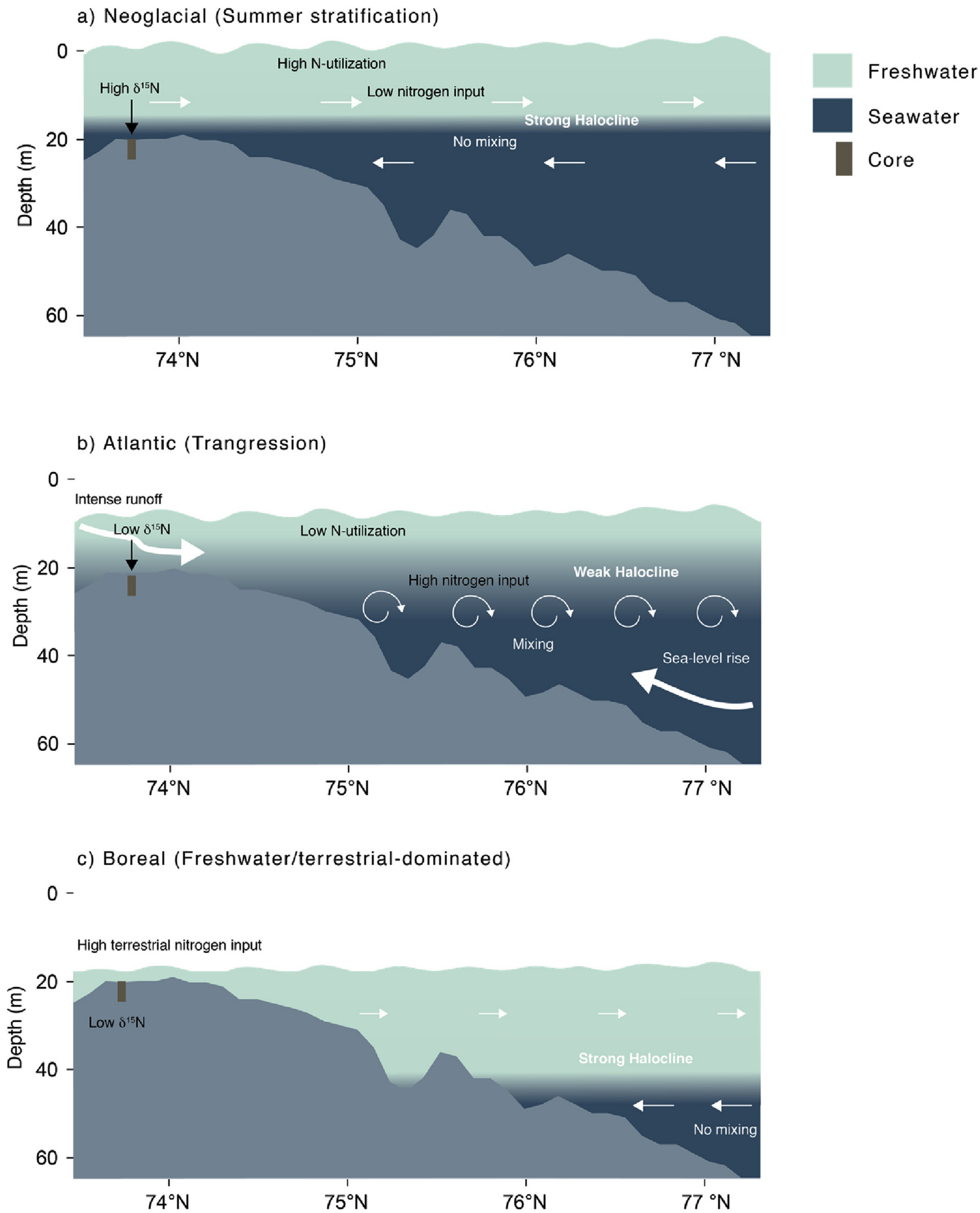

Fig. 4. Schematic of our conceptual model for the oceanography of the Laptev Sea shelf during the a) Neoglacial, b) Atlantic and c) Boreal period. The sediment core PM9462 is represented by the brown rectangle. The **c)** Boreal period was characterized by a high amount of freshwater and high terrestrial input (low $\delta^{15}N$) due to the proximity of the core to the river mouth. The high input of nutrient was probably also causing low nutrient utilization (low $\delta^{15}N$). Our coring site was dominated by freshwater. The **b)** Atlantic period was dominated by the transgression, sea-level rises and the gradual increasing influence of marine water at our coring site throughout the period. The gradual increase in marine organic matter drove the slight increase in $\delta^{15}N$ as the strong mixing due to the transgression probably kept the nutrient utilization low (low $\delta^{15}N$). Summer stratification was established only during the **a)** Neoglacial, after the sea-level reached a standstill, the strong halocline and decreased riverine input reduced the nitrogen input and increased the nutrient utilization (high $\delta^{15}N$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

hand, diatoms reconstruction suggest that the Neoglacial was slightly more saline (by about 0.3 psu) compared to the Atlantic period (Polyakova et al., 2005). Irrespective of the proxy used, the difference in salinity between the Atlantic and the Neoglacial seems to have been minor.

The transition to the Neoglacial is characterized by a sharp rise in $\delta^{15}N_{org}$ during the early part of the period followed by its stabilization at around 2.5 ka. Since the proportions of marine and terrigenous organic matter remained constant during the whole Neoglacial, the sharp rise in the $\delta^{15}N_{org}$ record around 4 ka is caused by an increase in the nutrient limitation rather than a change of source of nitrogen. The reason for this sharp increase is likely due to

the establishment of a strong summer stratification after sea-level rise came to a standstill and thus, enhanced nutrient utilization in the uppermost water masses in the Laptev Sea shelf (Fig. 4).

6. Evolution of the Laptev Sea stratification and sea-ice export by the Transpolar Drift (TD) system during the Holocene

The single most important factor that might control Arctic sea-ice production during the Holocene is the position and the size of large polynyas off Siberia, from which the Laptev Sea is considered the most important being closest to where the TD originates (Krumpen et al., 2016; Reimnitz et al., 1994; Zakharov, 1966). While changes in sea-ice coverage varied throughout the Holocene (Hörner et al., 2016), the underlying mechanism driving the variability throughout the Holocene is still equivocal. Increase in sea-level during the Holocene should be suspected to have an influence on the configuration on the Laptev Sea ice factory. However, no clear evidence was available to reconstruct the variability of this configuration. Here, we use our reconstruction of the summer stratification as a proxy of favourable condition for sea-ice production in the Laptev Sea and compare the result with a Holocene record of sea-ice algae production from the Laptev Sea and paleoceanographic data from the Atlantic end of the TD (Fig. 5).

6.1. Boreal and Atlantic (10—~4 ka)

The postglacial sea-level in the Laptev Sea rose by about 40 m during the Holocene transgression (Bauch et al., 2001b). The data suggest a relatively low nitrate-utilization and that most organic matter originated from land, which is consistent with previous findings using organic geochemical proxies (e.g., Boucsein et al., 2002; Fahl and Stein, 1999; Stein et al., 1999). The latter is also supported by our first-hand approximation of the proportion of terrestrial organic matter based on the $\delta^{13}C_{org,}$ which suggest that about 87% of the total organic matter was of terrigenous origin (see online research data). That assumption is coherent with the oldest part of the core where the $\delta^{15}N$ value is similar to the $\delta^{15}N$ value of particulate organic matter measured in the Lena River (4.6‰) (McClelland et al., 2016), corroborating the terrestrial origin of most of the organic matter during this period. During this period the water column was well-mixed with advection of nutrient-rich bottom water on the shelf due to the rapid sea-level rise (8–13 mm*yr^{-1}; Bauch et al., 2001b, 2001a). Unstable conditions were also observed in Fram Strait, with a weakly stratified water column and a strong influence of Atlantic water (Werner et al., 2016). During this relatively warm period, very low sea-ice algae production was reconstructed in Fram Strait and on the Greenland and Icelandic shelves based on IP_{25} (Fig. 5; Cabedo-Sanz et al., 2016; Müller et al., 2012; Werner et al., 2013). Moreover, the presence of warm Atlantic water was observed at the Reykjanes Ridge, suggesting a weak East Greenland current and a relatively northward positioning of the sub-Arctic front (Moros et al., 2012; Perner et al., 2017). Furthermore, a thin mixed-layer was observed in the Nordic Sea during this period, suggesting a weak import of surface freshwater from the Arctic (Thibodeau et al., 2017b). During the Holocene, modern sea-ice condition over the central Arctic, with a perennial sea-ice cover, was established around 5–8 ka (Cronin et al., 2010; Fahl and Stein, 2012). Thus, during this period, the Laptev Sea was characterized by a mixed water column and conditions unfavorable to intense sea-ice formation. This is illustrated by the slight increase of sea-ice algae production at the beginning of the Atlantic period, which become more important at around 6.5 ka but stays around 50% of the modern-day value (Fig. 5b). Coincidently, sea-ice export through Fram Strait was minimal, as

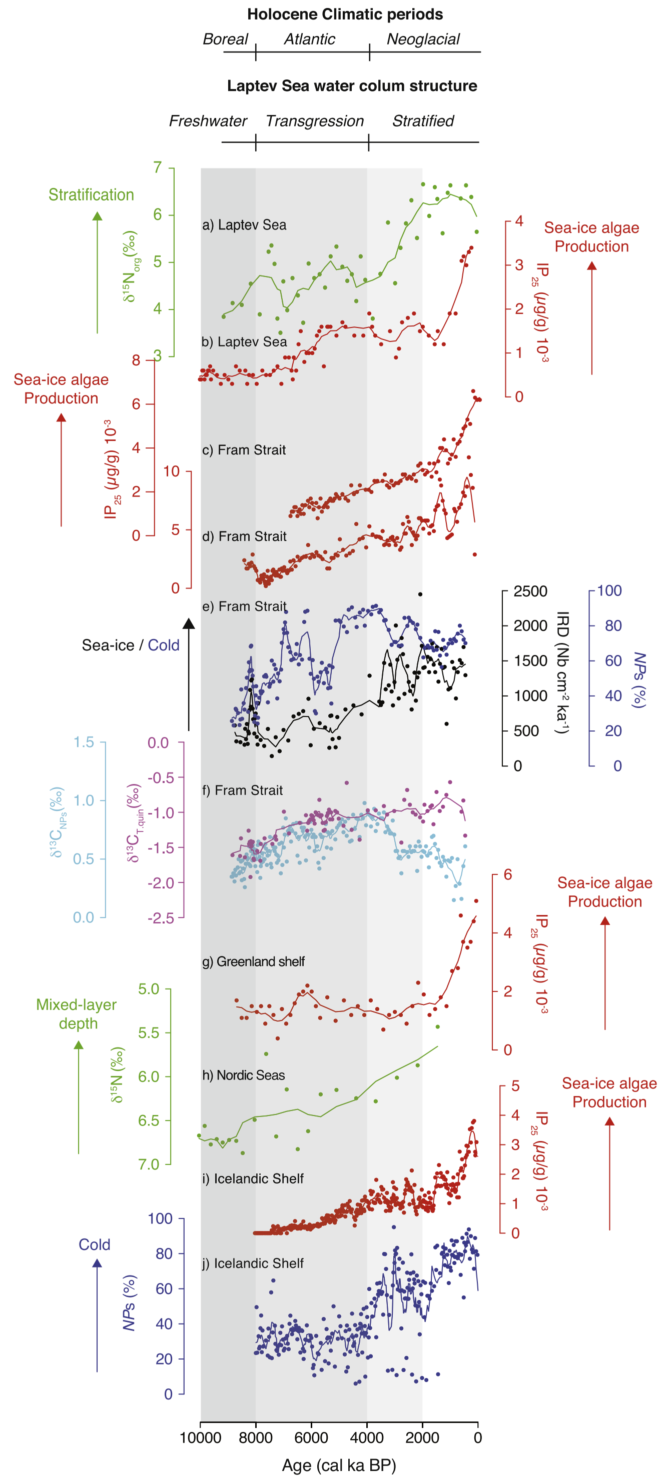

Fig. 5. Reconstruction of **a)** stratification in the Laptev Sea based on $\delta^{15}N$, **b)** sea-ice algae production in the Laptev Sea based on IP_{25} (Hörner et al., 2016), **c)** and **d)** sea-ice algae production in Fram Strait (MSM5-723-2 and 712–2) based on IP_{25} (Müller et al., 2012; Werner et al., 2013), **e)** sea-ice import and subsurface temperature in Fram Strait (MSM5-712-2) based on ice-rafted debris and polar planktic foraminifera *Neogloboquadrina pachyderma* sinistral (*NPs*) respectively (Werner et al., 2013), **f)** stratification of Fram strait (MSM5-712-2) based on $\delta^{13}C$ of *Neogloboquadrina pachyderma* sinistral and *Turborotalita quinqueloba* (Werner et al., 2013), **g)** sea-ice algae production over the Greenland shelf (PS2641-4) based on IP_{25} (Müller et al., 2012), **h)** stratification in the Nordic Seas (PS1243) based on $\delta^{15}N$ (Thibodeau et al., 2017b), **i)** sea-ice algae production over the Icelandic shelf (MD99-2269) based on IP_{25}, (Cabedo-Sanz et al., 2016), **j)** subsurface temperature over the Greenland shelf (MD99-2269) based on polar planktic foraminifera *Neogloboquadrina pachyderma* sinistral (Cabedo-Sanz et al., 2016). A 4-neighbors, 2nd order smoothing was applied to all dataset to see the general trend (solid lines).

suggested by the low IRD, and upper-ocean stratification was high in the Nordic Sea, suggesting a thin surface mixed-layer due to weak freshwater export from the Arctic (Fig. 5e, h).

6.2. Early Neoglacial (~4–2 ka)

After the sea-level reached its highstand at around 4–5 ka (Bauch et al., 2001a, 2001b), the condition became more stable in the Laptev Sea and a transition phase from the pre-4 ka unstable conditions toward the modern, highly-stratified, oceanographic setting commenced (Fig. 5a). This transition phase was characterized by an increase in nutrient utilization due to the progressive stabilization of the water column and river runoff as suggested by the consistency of most of the proxy data in this part of the core (i.e., no change in the marine to terrestrial ratio of organic matter input; Fig. 3). The ongoing stabilization of the water column here provided increasingly favourable conditions for the formation of polynyas and pack ice. Interestingly, there is no synchronous response in the sea-ice algae production over the Laptev Sea during this period (Fig. 5b). The 1800-year cycle identified in the IP_{25} record indicates that, at this timescale, there is a strong linkages between sea-ice formation and atmospheric processes like the Arctic and North Atlantic oscillations in the Laptev Sea (Hörner et al., 2016). A similar cycle have been identified in reconstruction of Arctic sea-ice drift during the Holocene (Darby et al., 2012). During the same period, sea-ice cover continuously increased in the high Arctic (e.g., Xiao et al., 2015), Chukchi Sea (Stein et al., 2017), Baffin Bay (e.g., Kolling et al., 2018), Fram Strait (e.g., Werner et al., 2013) and over the Icelandic shelf (Cabedo-Sanz et al., 2016) but only slightly over the Greenland shelf (Kolling et al., 2017; Müller et al., 2012). While climatic conditions became more favourable for in-situ sea-ice formation in the Arctic and marginal seas, the three-fold increase in IRD in Fram Strait (Werner et al., 2013) suggest a synchronous enhanced sea-ice export from the Arctic (Fig. 5e). Interestingly, the water column in Fram Strait also transitioned to a strongly stratified water column at around 3 ka as indicated by the difference between the $\delta^{13}C$ values of *Neogloboquadrina pachyderma* sinistral (*NPs*) and *Turborotalita quinqueloba* (Fig. 5f), with much cooler water at the surface as evidenced by the abundance of *NPs* (Fig. 5e). That change in stratification was also observed in the Nordic Seas, where the mixed-layer depth increased through this period, suggesting increased flux of freshwater from the Arctic (Thibodeau et al., 2017b). Much cooler surface water was observed over the Icelandic shelf and the Reykjanes Ridge linked with freshwater input and a greater influence of the sub-Arctic front (Cabedo-Sanz et al., 2016; Moros et al., 2012; Perner et al., 2017).

6.3. Late Neoglacial (2 ka to recent)

The complete stabilization of the modern summer stratification of the Laptev Sea was reached at 2 ka (Fig. 5a). We believe that it is also the onset of the present-day configuration of the so called “sea-ice factory” of the Laptev Sea. This configuration allowed the increase in sea-ice cover suggested by the increase in sea-ice algae production (Fig. 5b). However, the increase was not simultaneous probably because of the decrease observed in the 1800-year cycle in sea-ice cover that is driving most of the short-term sea-ice algae production variability (Hörner et al., 2016). Temperature reconstruction during this period suggests a local trend with warmer surface water and more stratified upper-ocean structure in Fram Strait while the Nordic Seas and the Icelandic shelve are characterized by cooler surface water (Cabedo-Sanz et al., 2016; Thibodeau et al., 2017b; Werner et al., 2013). Sea-ice algae production is generally increasing at all sites (Fram Strait, Greenland and Icelandic shelves), culminating at the end of the record when sea-ice margin reached its southern location (Perner et al., 2017) (Fig. 5). In this part of the record the IRD suggests a constant export of sea-ice from the Arctic to Fram Strait (Fig. 5e). Moreover, a shift in the mineral source region from Arctic to Fjord at around 1.2 ka in core from East Greenland shelf might be related to increased outflow from Fjords and is correlated with glacier advance in Greenland indicating a widespread increase in sea-ice production (Kolling et al., 2017; Solomina et al., 2015).

7. Paleoclimatic implications

Our results highlight the fact that favourable conditions for sea-ice formation in the Laptev Sea after 2 ka are concomitant to enhanced export of sea-ice via Fram Strait and the installment of modern-like conditions along the TD up to the central Nordic Seas. This also implies a change in the Arctic atmospheric circulation system after the mid-Holocene as it drives the TD. Thus, we suggest that the establishment of a stable water column structure in the Laptev Sea, after the Holocene transgression, had a significant impact on the sea-ice dynamic over the Arctic and on the freshwater export via Fram Strait. This increase in freshwater export probably contributed to regulate climate during the last 2000 years through its impact on Artic heat budget and on polar North Atlantic stratification. While more work is needed to disentangle the exact drivers of sea-ice variability throughout the Holocene, we show here that the onset of coastal Arctic sea-ice factory probably played a role, along atmospheric processes, in the production of sea-ice and its export toward the North Atlantic. This needs to be considered when trying to reconstruct Arctic Ocean sea-ice drift and coverage based on paleo-data and/or modelling (e.g., Funder et al., 2011).

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